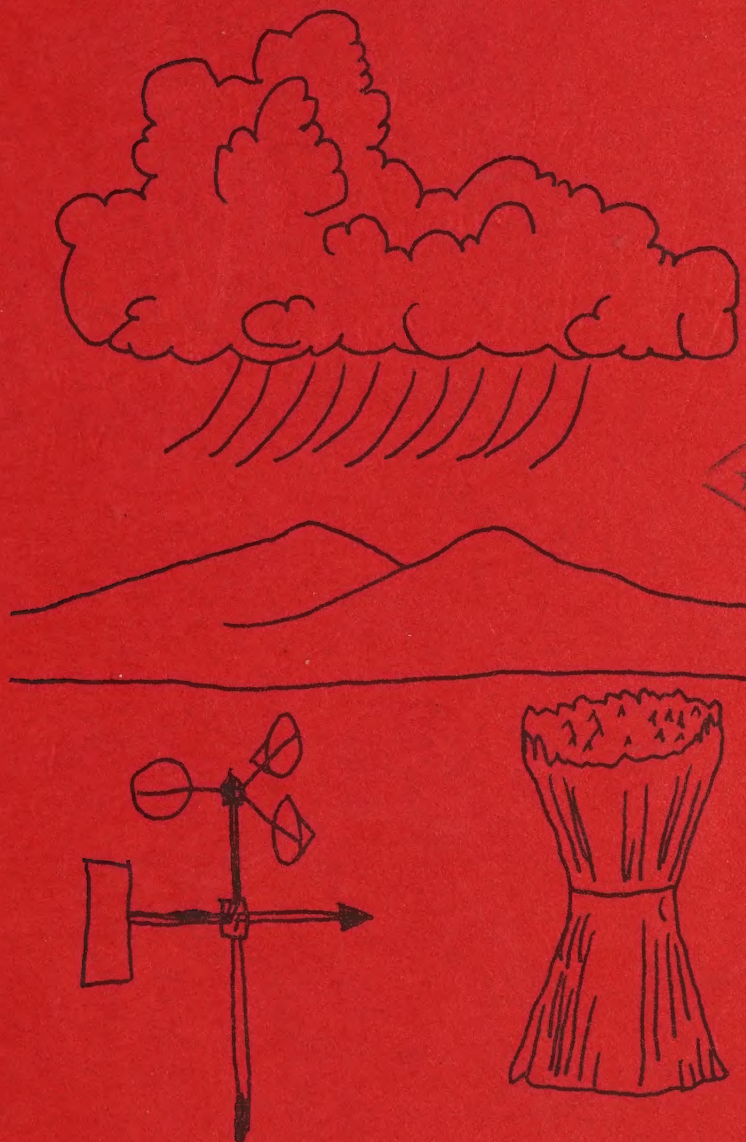
AGRICULTURAL METEOROLOGY

A Brief Literature Review & Bibliography

by

J. L. Dionne, Geo. W. Robertson, & R. M. Holmes



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Agricultural Meteorology

A Selected Bibliography

FOREWORD

This brief review of research on and related to agrometeorology was designed to cover the high lights and very general aspects of the problem, and suggest possible approaches to future investigations.

The bibliography lists papers according to subject. References in the text to these sections (A to P) appear in parenthesis with the date of the literature review. For example "Lundegordh (1931 A)", refers to section "A" in the bibliography where, "Lundegordh 1931" appears.

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AGRICULTURAL METEOROLOGY

Literature Review

INTRODUCTION

Agricultural meteorology refers to the study of the processes by which plants selectively integrate the effect of weather. (Smith 1920, A); its purpose is to determine the influence of each meteorological factor on crops.

II PLANT RESPONSE TO PHYSICAL FACTORS UNDER CONTROLLED CONDITIONS

Before agronomists can establish weather-plant relationships the role of the individual meteorological factors in plant life must be known. This is partially achieved by holding all factors constant except the one being studied. Such studies are mainly carried on in greenhouses or growth chambers. The first part of this review will deal with experiments of this kind. Although this approach deals with plant physiology, it yields vital information on how weather affects plant growth and development. According to Penman (symposium on meteorology 1955 a) a clearer understanding of how plants selectively integrate the effect of weather is imperative before we can show how the weather affects plant growth and development. The three meteorological factors most often studied are temperature, light and moisture.

A Light Factor

The light factor shall be considered first and shall be discussed under: 1) intensity, 2) quality, 3) duration.

(1) Light Intensity

The papers reviewed indicated that light intensity is usually not critical for a plant growing under field conditions.

The influence of light intensity on the rate of photosynthesis was investigated by Hoover, et al. (1933, G). They found photosynthesis to increase rapidly with light intensities up to 1000 foot candles.

Assimilation curves were established by Lundegordh (1931, A). He plotted the amount of CO_2 assimilated by shaded leaves, against light intensity expressed in percentage of full sunlight. He showed that assimilation increases with light up to intensities ranging from 1/10 to 1/3 of full sunlight. Increases in assimilation were not observed at higher intensities. However, Meyer and Anderson, (1952, A) pointed out that higher light intensities could be beneficial to crops because bottom leaves of a heavy crop would receive more light during bright summer days. This is in accordance with Papp (1926, E) and Shirley (1929, 1936, E). Dry weight and percentage of dry matter in the tops increases with increasing light intensity up to full sunlight, provided other factors are not limiting.

Plant physiologists agree that a plant gains weight provided the amount of carbohydrate oxidized is exceeded by the amount built up in photosynthesis. Plants have survived at light intensities as low as 26 foot candles (Papp 1926, E).

(2) Light Quality

Meyer and Anderson (1952, A) concur with most scientists who have investigated light quality and its effect on plant growth. They state that light from the complete solar spectrum is more beneficial to plant growth than light of any particular wave length.

(3) Duration of light or daylength

Little attention was given to duration of light or daylength until 1920 when Garner and Allard (1920 E) studied photoperiodism. These scientists had noticed that Maryland Mammoth tobacco only flowered and matured during the winter at Washington. In an attempt to find the reasons for this peculiar behaviour, plants were subjected to many combinations of nutrients, temperature, light intensity and quality in the greenhouse during the summer. It was still impossible to bring the tobacco into flower. A series of experiments was conducted in which Maryland Mammoth tobacco and soybeans were submitted to different photoperiods, by putting the plants in dark chambers at special times in the afternoon and by taking them out again in the morning. This induced the flowering of tobacco.

The discovery of photoperiodism stimulated much research in this field. For a complete review on this subject the reader is referred to "Vernalization and Photoperiodism" edited by Murneek and Whyte (1948, G).

Plants are arbitrarily divided into three groups according to their response to daylength.

1 - Long day plants requiring a day longer than 12 hours to produce flowering.
2 - Short day plants requiring a day shorter than 12 hours to flower.
3 - Indeterminate plants having no critical photoperiod.
Most of these plants are vegetative and flower over a wide range of daylengths.

Below is a list of some economic plants classified according to photoperiodic response:

Long day plants: Oats, wheat, barley, rye, red clover, timothy, spinach, radish, beets, sugar beets, carrots, lettuce, cabbage.

Short day plants: Tobacco, soybeans, millet.

Indeterminate: Tomato, squash, cucumber, buckwheat, cotton. The mechanism of photoperiodism has been studied extensively but shall not be considered here.

B Temperature Factor

Lundegardh (1931, A) once stated, "Temperature is master factor in the distribution of vegetation over the earth, though its action is always interwoven with those of light and water". He reviewed the literature on the influence of temperature on (1) growth, (2) assimilation and (3) respiration of plants. These three physiological functions respond to temperature in a similar though not identical way. There is a minimum temperature below which growth, assimilation and respiration is not possible, then, as temperature increases above this minimum, the rate of these three physiological functions increases until it reaches a peak at a temperature called "optimum". Above this temperature there is a decrease in growth, assimilation and respiration until they stop completely at a high temperature called "maximum". Thus if amounts of growth, assimilation, and respiration are ploted individually against temperature, three similar curves will be obtained, with its own maximum, minimum and optimum.

The following table illustrates variations of minimum, maximum and optimum growth temperatures of plants:

Table 1

Plant	Minimum Temp.	Optimum Temp.	Maximum Temp.
Wheat	32°F	84.2	107.6
Corn	48.2	93.7	114.1
Cucumber	44.6 to 46.4	87.8 to 98.6	111 to 122

Lundegardh (1931 A) gave the optimum assimilation temperature for the following Plants:-
Potatoes 68°F, tomatoes 68°F, sugar beets 66°F, beans 80.6°F.
For most plants, the optimum temperature for assimilation is between 59°F to 80°F.

Knowing these different growth curves and the cardinal temperature points (max. min. opt.) for each plant, it may be possible to predict the response of crops to the climate of a given locality.

The influence of temperature on vegetation has been summarized by Lundegardh (1931 A). The temperature climate, therefore, falls into four ecological periods, more or less corresponding to the seasons.

1 - Growth period (spring) when an increase of temperature has a consistently favorable effect at any rate up to temperatures of 30°C (86°F).

2 - Assimilation period (summer - autumn) when high (but not too high) day temperatures and low night temperatures are most favorable.

3 - Fruit formation, (autumn) when the most favorable climate is one with moderate day and night temperatures.

4 - After ripening period, (winter) when low temperatures, so long as they are not too low, are advantageous. (From Lundegordh, "Environment and Plant Development", page 98.)

C Light and Temperature Interaction

A careful review of papers on the influence of light and temperature was made by Murneek and Whyte (1948 G). They concluded that plant response to daylength is affected by temperature, and conversely, that photoperiod influences the response of plants to temperature. It is also reported by R. O. Whyte (1946, A) that in several instances, high temperatures compensated for short days in plant development.

According to Demolon and Geslin (1943, G) solar radiation should be accompanied by temperature measurements when characterization of a climate for plant adaptation is involved.

The light temperature interaction has been investigated for several plants.

The response of potatoes to light and temperature was studied by Werner. (1934, G).

Description of temperature and light requirements of common vegetables can be found in papers by Milthrope and Horwith (1943, G).

Vlric (1952, G) studied the influence of light and temperature on the growth and development of sugar beets. He observed that night temperature is more important than day temperature in sugar production, the optimum being 57°F when the daylength was 10 to 14 hours.

The interaction of temperature and daylength was studied by Reath and Wittever (1952, G) by noting the effects of temperature and photoperiod on the development of pea varieties. The results obtained by these workers are in table 2.

The following table indicates that high temperature can compensate for short days in bringing peas to flower. Long daylengths compensate for low temperatures. Note that temperature and daylength have a marked influence on the height of pea vines.

Other references are cited, (see section G) on the importance of temperature vs. light interaction in plants.

Table 2: Effect of temperature and photoperiod on days required for flowering, and vine heights of pea varieties.

Variety	Days for flowering				Vine heights in centimeters			
	50°F Night Temperature		60°F Night Temperature		50°F Night Temperature		60°F Night Temperature	
	9 hrs.	16 hrs.	9 hrs.	16 hrs.	9 hrs.	16 hrs.	9 hrs.	16 hrs
Alaska	61	52	37	37	127	115	103	77
Idaho Whites	87	64	56	46	168	153	177	142
Surprise	63	55	37	37	132	134	115	123
Early Perfectah	90	71	69	50	106	106	119	69

D Water Factor

There is a maximum, optimum and minimum water factor for crop growth. Lundegordh (1931, A) reports experiments by Metscherlich and Gehrmann in which different amounts of water were given to plants growing in pots. Generally, the yields were found to increase with increasing soil moisture up to the point where aeration was limiting.

III PLANT RESPONSES to METEOROLOGICAL COMPLEX

Three meteorological factors, have been considered in relation to their influence on crops. These influences shall now be considered under natural conditions. Meteorologists have data such as rainfall, temperature, solar energy, and windspeed. The agronomist has plant yield, growth, and development data. The following discussion will attempt to illustrate how these variables are correlated.

The effect of weather on plant growth was noted very early. The Agricultural Commission of Ontario (1881 A) received a report from a meteorological observer who pointed out that weather probably affects agricultural crops through temperature fluctuation, humidity, wind, and rainfall. In 1916 (1916 A) weather was not studied in relation to agriculture and all meteorological measurements that should be recorded in connection with such studies were listed. Cleveland Abbe (1916 A) has reported on the early work. His monograph is entitled "First Report on the relation between Climates and Crops", and consists of a fairly complete review of agro-meteorological work done through the world up to 1905.

Present problems facing agricultural meteorologists have been surveyed by Penman (1949 A). He divides them into three groups:

1 - Statistical problems including forecasting of weather for use in planning farming operations, and the forecasting of crop yields from weather data.

2 - Biological problems dealing with growth and spread of disease. A wider knowledge of techniques for use in micrometeorology is required.

3 - Physical problems made up largely of transport problems in the building up of plant and animal environments; for example determining evapotranspiration from a solar energy balance sheet. Evapotranspiration is useful for simplification of irrigation practices.

The first step seemed to be the recording of regular meteorological observations on experimental farms and other agricultural stations. Data from several years observations of air temperature, relative humidity, rainfall, hours of bright sunshine can be found.

A Micrometeorology

Lately, observations were taken near the ground in an effort to measure the climate of plants. (The term microclimatology refers to the detailed study of climate near the ground, below 2 meters.) Microclimatology was initiated by Kraus in 1916 and in recent years many scientists have become interested (section C). For further information on the subject the reader is referred to the book "The climate near the Ground" by Geiger. (1950 C). A paper by Broadbent (1950 C) entitled "The Microclimate of the Potato Crop" is noteworthy. Temperature and humidity were measured within and above a potato crop at heights of 10, 20, 30 and 60 cm. and windspeed was measured at 20, 30 and 200 cm. above the ground. These data were compared with the regular meteorological data. On sunny days the temperature was higher within the crop than above the crop. Humidity was also higher in the crop during the day. Temperature and humidity contrasts were reduced by air movement within the crop where wind speed was changing every few seconds. The temperature of the plant leaves was also different from the air temperature. The temperature of strawberry leaves was measured by Seely (1917 C), by wrapping them around a thermometer bulb. This crude method revealed that leaves are often ten degrees warmer than the air.

The temperature of plants can be calculated from existing meteorological data. Robertson (1953 A) developed a formula for calculating plant temperature using wind speed, vapor pressure, solar radiation and air temperature. According to this formula, Millet temperature at Ottawa was 4.5°F higher than air temperature.

B Phenology

A new effort has been made recently to bring together phenological information (section D). Thus dates of seeding, emergence, heading, maturity of crops are related to meteorological data. An English society records phenological data noting insect and biological phenomena which occur periodically.

The data collected in the British Isles in 1937 are presented in a report made by Major H. C. Gunton (1937). Such a collection of data is exceedingly difficult to analyse. Part of the English phenological data were analyzed by Smith (1938). He concluded, after a statistical study, that flowering was affected by temperature. Warmer temperatures caused plants to flower early.

Heat and light requirements of several economic plants have been determined with the aid of phenological data by Nuttonson (1948).

Relationships between climate and vegetation have been studied by several other methods which are classified by Geslin (1937 A), into 1) statistical, and 2) experimental.

IV METHODS OF EXPERIMENTAL ANALYSIS

A Plant Responses and Statistical Methods

Statistical manipulation attempts to correlate meteorological factors and crop yield. This method assumes there is a critical period in plant life where environmental conditions must be optimum if maximum crop yield is to be obtained. Therefore the growing season is broken down in periods of months, weeks, days, etc. Correlations between yield and the mean of a given meteorological factor for each of these periods is calculated. The period in which the highest significant correlation coefficient is found is the critical period as far as that factor is concerned. Statistical methods are used mainly in Canada and the United States.

Certain meteorological factors are sometimes found to be beneficial, and other times harmful. For example rainfall will be beneficial in dry countries and harmful in humid regions.

A summary of some of the findings reported in numerous papers published in Europe and America will be considered. Climatic requirements of some important economic crops are given.

1. Wheat

In dry regions such as Manitoba, autumn rainfalls are needed to build up soil moisture reserves for the next growing season. At the beginning of its growth, wheat requires just enough water to maintain growth but the water requirement increases and is at a peak at heading time. Then each additional inch of rainfall results in an increase of 4 bushels per acre. (Davis and Pallensens 1940). Hopkins (1935 B) gives lower figures.

The heat requirement of wheat is different from its moisture requirement. Warmth is required at germination time, but cool temperatures are best up to a few days before maturity. Then several days of extra heat is needed to mature the crop.

2. Corn

For optimum yields, moisture reserves should be high during the growing season until September. In the corn belt States, an inch of rain above normal, yields an increase of three bushels of corn per acre. The optimum maximum temperature of corn should be between 75°F and 85°F, depending upon the rainfall. However, night temperature should not be lower than 55°F (Davis and Harrell 1942 B).

Integral regression methods are often used to study the effect of weather on yields of wheat and corn. Yield is assumed to be a function of weather which varies continuously with time. This is represented by a curve showing the effect of a given meteorological element on yield at any time during the growing season. Housemon (1952 B) described the statistics involved.

3. Oats

Many studies have related oat yields and weather. Vacks (1945 B) studied the effect of temperature and rainfall on oat yield in 13 regions in Southern Ontario. A cool, wet period through June and July is important for high yields.

4. Other Crops

Some crops grown in Canada require a cool and humid summer. Among these are barley, rye, timothy, and some hay crops.

Publications in agrometeorology in which statistical methods have been followed are numerous (section B) but they are chiefly of local interest and can be applied only to these regions in which the work was done.

B Plant Responses and Experimental Methods

The effect of local weather on yield of cultivated plants has been considered. The information given by such studies are of most value to the agriculture of the regions studied, and applications to other areas are difficult. In order to obtain results of general application, all variables must be kept at a minimum. According to Geslin (1937 A), the experimental methods used must permit the definition of growth laws on one hand, and the determination of specific climatic requirements for all stages of development on the other. It would then be possible to determine the optimum climate of a crop. Papers on response of plants to weather as determined by experimental methods shall be reviewed under: 1) - temperature, 2) - light, 3) - water.

1. Temperature Factor

Temperature determines the rate of most physiological reactions in plants.

(a) Heat Unit Theory

According to the heat unit theory, a plant requires a definite quantity of heat in order to reach certain stages in its development. Only part of the heat received every day is used since a minimum amount of heat is required before the plant progresses in its development. This indicates a base temperature over and above which heat is accumulated every day until a constant is reached. This would mark a certain stage in the plants development. Thus, if a plant has a base temperature of 42°F and the mean temperature on any one day is 62°F, 20 degree days have accumulated. If 1500 degree days are required for heading, the plant should respond when this amount had accumulated. This theory is used in forecasting the maturity date of canning crops. (section F) Some base temperatures are: Grains 32°, peas 40°, corn 50°, spinach 35°, pumpkins 55°, and lima beans 50°F. The thermal constant varies somewhat depending upon soil type, fertility, depth of seeding, etc.

Exponential heat indices (Livingston 1916 F) are based on similar principles but instead of simple base temperatures, heat units are calculated according to the following formula:

$$v = 2^{\left(\frac{L - 40}{18}\right)}$$

where v is the number of daily heat units accumulated, and L is mean daily temperature. As in the previous system, a constant number of heat units is required before plants reach heading, maturity, etc. According to Appleman (1921 F), this method would be superior to the previous one in forecasting the date of maturity of sweet corn, but Katz (1952 F) found the two methods to be of equal value in forecasting maturity of sweet peas.

(b) Temperature Growth Laws (section f)

Geslin et al (1931 F) investigated the response of wheat to weather, and found that the length of time from planting to emergence of the plant was proportional to soil temperature and depth of the seeding. The length of the germination period varied according to the following equation:

$$XY = 40.6\ (100\ Z)$$

where Y is the length of germination period, X is mean soil temperatures, and Z is depth of the seeds in soil.

Leaf growth is also proportional to temperature according to the following equation:

$$A = 0.73T, \text{ where}$$

A is the growth of leaves as measured by their length. T is the temperature in degree centigrade.

Temperature also affects wheat development. According to Robertson

and Dionne (1955 G) the length of time from heading to maturity of Marquis wheat is mostly dependent on temperature. The number of degree days required from heading to maturity is 922, with a base temperature of 38°F.

A study of the effect of temperature on sugar beets was made by Godard (1937 G). The increase in size of sugar beet roots was proportional to the soil temperature. The cooling of the soil in the fall restricted root growth.

2. Light Factor

Light is interrelated with temperature in its influence on plant growth and development.

After many years of investigation, Geslin (1946 A) published his concept of "Constants Heliothermique" or "Law of the Product of Temperature by Day Light Hours". It was observed that a given amount of dry plant material required a constant value of the product TL (temperature X day light hours).

Wheat development was also found to follow the "Law of Products". A constant number of TL units was required for each stage of development. Thus there were 142 and 135 units needed from planting to heading and heading to maturity respectively.

Robertson and Dionne (1955 G) also found, from data gathered in North America, that the length of the period, emergence to heading of Marquis wheat, was proportional to temperature and daylength, and that 30600 TL units over and above 330 were required to head out Marquis wheat. The temperature was measured in degrees F.

Solar Radiation was also investigated by Geslin (1946 A). The action of temperature and total solar radiation was studied in relation to leaf elongation of wheat and the following relationships were obtained: (a) At constant solar radiation, leaf elongation of wheat is proportional to temperature. (b) At constant temperature elongation of wheat leaves plotted against solar radiation is parabolic.

Therefore, leaf elongation of wheat is proportional to the product of the temperature, the square root of the total solar radiation and a factor K defined as $K = L X \sqrt{R}$ where L is daily total solar radiation. There is a linear relationship between leaf elongation and K. This indicates that leaf elongation is proportional to K.

Water Factor

Water factors largely determine plant distribution on the earth (Lundegardh 1931 a). The life and growth of plants depends on the total water balance that is, the relationship between the amount of water which the plant takes up and the amount it loses by transpiration. Normally the ratio, water uptake/transpiration, cannot sink for long below unity. But this ratio depends greatly upon meteorological factors such as rainfall, relative humidity, solar radiation, evaporation, etc.

Much effort is spent estimating the water used by plants (uptake and transpiration).

Briggs and Shantz (1914 I) determined the water requirement of many economic plants. The plants were grown to maturity in large galvanized iron pots having a capacity of 115 kg. of soil. These pots were provided with a tight fitting cover having openings for the stems of plants. Pots were weighed two or three times weekly and the loss in weight was recorded as water used by plants. The water requirements were expressed in pounds of water used to produce one pound of dry matter or grain. The following list gives the water requirements of some plants:

Table 3 Water requirements of plants (pounds of water per pound of Dry Plant material)

Crops	Total dry matter	Grain
Millet	310	959
Corn	368	
Sorghum	322	
Wheat	513	1205
Barley	534	1050
Oats	597	1229
Buckwheat	578	
Rye	685	
Sugar Beet	397	
Potato	636	
Cabbage	539	
Pumpkins	834	
Cantaloupe	621	
Sweet Clover	770	
Beets	788	
Clover	797	
Alfalfa	831	

These values vary under different environments.

(a) Evapotranspiration

Many agrometeorological publications deal with evapotranspiration (amount of water transpired by plants plus that evaporated from the soil). Godard (1949 I) measured transpiration of corn in a way similar to the one used by Briggs and Shantz and concluded that transpiration was proportional to the temperature, and square root of the evaporating power of the air as measured by a Piche evaporimeter.

Recently, studies on utilization of water by plants has been conducted at the Soils Laboratory at Swift Current (1949 K). It was observed that about 10.5

inches of water are needed to produce 14 bushels of wheat and each additional inch of water increased the yield by 5 bushels per acre. When water use was limited to 5 to 6 inches, there was a crop failure. The more water that was available to plant the less it took to produce one pound of dry matter; therefore under favorable soil moisture conditions there was a more efficient use of water. The highest rate of water use occurred from heading to a few days before maturity of Marquis wheat.

Water use by plants is exceedingly difficult to measure but it can be estimated using meteorological data. Robertson (1953 I) has developed and calibrated an evaporimeter. The readings may be converted into inches of water evapotranspired.

Some years ago the concept of potential evapotranspiration was developed. Potential evapotranspiration is the maximum amount of water which can be transpired by plants and evaporated from the soil when soil moisture is not limiting.

Formulae have been devised by Thornwaite, (Mather 1950, I), and Penman (1950, I) which enable calculation of potential evaporation from meteorological data. Thornwaite's formula is based on air temperature, whereas Penman's formula takes temperature, solar energy, hours of bright sunshine, vapor pressure deficit and wind speed into consideration.

Recently potential evapotranspiration has been measured directly under field conditions. Many types of evapotranspirometers are in use. Grass is grown in tanks filled with soil kept at field capacity. The amount of water added every day to maintain field capacity is assumed to be equal to evapotranspiration, or water used by plants and evaporated from the soil. Water can be added by subirrigation or sprinkler. Evapotranspiration measurements have been taken in many parts of the world and much of the data been compiled by Mather (1954 I) of the Johns Hopkin's University Laboratory of Climatology. Potential evaporation measurements indicate the water used by a crop and are used to keep soil moisture budgets.

Program of Studies in Agrometeorology

Interest in agrometeorology has been revitalized. A summary of the program for the Agrometeorological Service, in U.S.A. has been suggested by Beall (1954 a):

1 - Establish key stations for short and long range weather forecasts adapted to agriculture. These stations would give all meteorological data of interest to farmers and advise about steps necessary for the coming weather.

2 - Establishment of meteorological specialists in cooperation with the Agricultural Experiment Station staffs to work on research problems in agrometeorology.

3 - Broadcast five day agricultural forecasts three times a week.

4 - Seasonal forecast development: A seasonal forecast would be beneficial to farmers in their planning for the forthcoming season.

5 - Publish weekly and seasonal weather crop reports and summaries.

6 - Phenological Data Survey: Giving dates of emergence, budding, fruiting, harvesting for various species of plants - this will help to establish the plant weather relationships.

7 - Crop weather research and agricultural weather compilations of weather data at a national weather record center.

8 - Installation of agricultural weather instrument at selected stations. Soil temperature and moisture, and dew deposit measurements could be made at these stations.

9 - Development program for improvement of weather instruments for agricultural use. Work should be done on such instruments as soil thermometers, dew meters, evaporimeters, soil moisture meters, radiation meters, etc.

10 - Evaluation of weather control measures which would be of economical interest to all farmers.

A great deal of work is yet to be done before such a proposal can be put into effect. It would represent a great achievement for the agrometeorologist, and weather would no longer be something that everyone just "talks about".

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